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**INNOVATIVE CONCEPTS FOR PERFORMANCE EVALUATION & QUALITY
ASSURANCE OF CERAMIC TILE ARMOR SYSTEMS (U)**

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ABSTRACT (U)

(U) The use of high purity ceramics in armor applications continues to gain popularity across all threat levels. While ceramic component manufacturers continue to make larger panels (near net shape) a reality, the use of ceramic tile arrays will continue due to ease of tile manufacturing and the necessity for multi-hit protection. Nevertheless, the use of ceramic tile arrays in armor presents several questions related to threat defeat performance and quality assurance for the desired system. Unlike a monolithic metal, the ability of a ceramic tile armor system to defeat a threat is dependent on the location of the impact with respect to the tile array. Further, the ability of ceramic armor systems to withstand multiple impacts is significantly less than for that of a monolithic metallic armor. This work presents a testing method which exploits the multi-hit capabilities of a system and can be applied to any shot pattern or sequence. Finally, issues of quality assurance for the ceramic tiles used in armor applications are presented. While current techniques for inspection are in place (dye penetration, X-ray, etc.), the criteria for acceptance remains questionable as related to design intent and performance. An innovative technique involving the use of ultrasonic mapping is shown to enhance the inspection process over current methods.

(U) Acknowledgements

(U) The authors would like to thank the following people for their individual efforts to support this work as well as the respective companies for their important contributions. Bob Herold from Ferro Corporation donated ceramic tiles and assisted with ballistic testing costs. Bruce Stetler from Byron Laboratories performed the ultrasonic mapping and x-ray of ceramic tiles used for armor samples.

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(U) Introduction

(U) Ceramic materials are used in multiple component armor systems to defeat a wide range of direct-fire threats. The inherent hardness, compressive strength and relatively low density are some of the properties which make ceramics appealing for defeating armoring piercing (AP) threats. However, high purity ceramics typically cannot be used as a stand-alone material because they are brittle. For this reason, they are often adhered to a more ductile, energy-absorbing backing material which also serves the role of supplying support to the ceramic during the impact event. The armor systems are constructed by bonding an array of smaller ceramic tiles (i.e. 2"x2" square) onto a continuous backing plate or laminate. The use of smaller ceramic tiles allows the preservation of adjacent areas of an armor panel to support multiple direct-fire impacts. For example, if one tile is impacted, the damage should be contained to that tile leaving the surrounding tiles intact to defeat additional shots in neighboring areas. Nevertheless, the neighboring tiles may only appear to be intact but may contain micro cracks. In fact, the dynamic deflection of the entire panel resulting from an impact may cause tile cracking and/or degradation of the adhesive bond in areas not immediately adjacent to the impact location. The method of testing selected for this study attempts to exploit this characteristic.

(U) The inspection standard commonly used to date contains dimensions based on what the manufacturers can hold in their processes, not what is acceptable on a ballistic performance level. In this discussion, we will begin to scrape the surface on ways to develop dimensional accept/reject criteria for ceramic tiles at a high value to the customer by implementing quality checkpoints throughout the manufacturing processes. This allows you to screen and eliminate as many discrepancies or suspect tiles at the front end of your process before investing labor hours and other material costs into your product.

(U) Our current process starts at the tile manufacturing facility with close monitoring of the production and firing processes. The first set of checkpoints consists of density checks and statistical dye penetrant testing. These are performed on each lot or batch and are used to detect any openings or flaws to the surface of the tile. The next checkpoint is a 100% visual inspection, using dimensional and chip specifications from the manufacturer, prior to layout of the tiles. These two sets of checkpoints give some confidence that the tiles used in the final product are of high quality. But there is still room for improvement.

(U) Inspection Methods for Ceramic Tiles

(U) Prior to ballistic tests, the ceramic tiles were tested Nondestructively and the data recorded in order to see what the results from a good homogenous tile might differ from one with inclusions or voids. The tiles were chosen at random and visually inspected for external abnormalities. For this paper two nondestructive test methods were

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chosen to view internal abnormalities. The two methods are described in the following sections.

(U) Radiography is a nondestructive inspection method based on the differential absorption of penetrating radiation – either x-ray (electromagnetic) or gamma ray (particulate radiation) – by the object of interest. Because of density differences and thickness variations or differences in absorption characteristics caused by variations in composition, different areas in the tiles will absorb more or less of the radiation. The unabsorbed radiation then passes through the test piece and can be recorded on film, photosensitive paper, or viewed on a fluorescent screen. For the purposes of testing the ceramic tile in this paper, film was selected. 50 tiles were chosen randomly and numbered for identification purposes and placed on an adhesive backing material in lots of 25. A Phillips model 420 was used as the x-ray generating source and Agfa D-4 film was the exposed medium. The images from the x-ray inspection were not included because they could not be converted to digital images in a timely manner.

(U) We are starting a new innovative method of testing ceramic tiles to help increase our confidence in the end product... “ultrasonic mapping”. Several methods of ultrasonic testing are available in industry today. Two methods (a) Contact and (b) Immersion are the most common used in industry. For our purposes we chose Immersion for a couple reasons, 1) the output data is easily interpreted and 2) it can be automated in order to ensure 100% coverage. The same tiles used in the radiographic inspection were scanned in an IRT LS-200 Immersion System. The transducer used was a focused 10mhz frequency crystal 3/8” in diameter focused at 3”. The effective beam width of the transducer was approximately .028” in diameter. The tiles were indexed at .020” thus creating a 30% over lap. 10% of a lot is selected for sampling, when received from the manufacturer. If any of the sample lot is rejected, the rest of the batch is suspect and will be subjected to 100% ultrasonic submersion inspection. Only accepted tiles will be used from this lot.

(U) There are also several inspection methods for ultrasonic mapping. The inspection method we selected was the Pulse-echo method using the C-scan display. The pulse echo method is the most widely used of all ultrasonic techniques. It works by the operator selecting a constant interval between pulses. The electronic clock triggers the signal generator, which sends short bursts of high-frequency alternating voltage. At the same time, the clock activates a time-measurement circuit connected to the display device. The mechanical vibration or ultrasound is introduced into the test piece through a couplant, in our case, water, and travels by wave motion through the test piece at the speed of sound. When the pulse of ultrasound encounters a reflecting surface that is perpendicular to the direction of travel, ultrasonic energy is reflected and returned. The returning pulse travels along the same path and at the same speed as the initial pulse, but in the opposite direction. The beam will travel through a material until it strikes an interface, which could represent a flaw or the opposite side of the entry surface. The amount of energy reflected is a function of (a) the nature and orientation of the interface and (b) the acoustic impedance of the reflector. Energy reflected from various interfaces may be used to define the presence and location of flaws, the thickness of a material, or

the depth of a flaw beneath the surface. The C-scan display records these echoes from the internal portions of test pieces.

(U) Interpretation of the pulse-echo data is relatively straightforward. The C-scan records the front reflection, while internal echoes or loss of back reflection, or both, are interpreted as flaw indications. Flaw depth is measured as the distance from the front reflection to a flaw echo, the latter representing the front surface of the flaw. The darker the color the lower the amplitude (less energy) of the reflected signal is returned and the brighter the color is a higher amplitude (more energy) signal returned.

(U) There are several other advantages to this testing method. For example, it works well with the smooth surfaces and regular shape of the tile. In addition, excellent penetrating power allows for detection of even the smallest inclusion or void with better accuracy in identifying their size, location and shape.

(U) Sample Construction & Ballistic Testing

(U) In order to evaluate the performance of an armor system, representative samples were constructed out of a staggered ceramic tile array (see figure 1). The sample panels were made from the following components: (1) 15" x 15" 1 ply rubberized aramid (front cover), (36) ceramic tiles, (6) 1" x 2" steel inserts, (2) "L" shaped brackets, (1) 15" x 15" aluminum backer and Class A1/2 polysulfide adhesive. The steel inserts were used to allow the edge of the panels to be flush. The "L" shaped brackets were used to give the tiles support along all edges and for clamping purposes. Aluminum was selected as the backer because it is commonly used to support ceramic tiles in ceramic armor systems. The "clean" ceramic tiles were supplied by the Ferro Corporation. The tiles had the dimensions of 0.330" x 2.0" x 2.0" and were constructed of 99.5% Al₂O₃.

Figure 1 – Panel Construction

Figure 1. Sample panel of ceramic armor system (U)

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Precautions were taken to ensure a constant bondline and web spacing was maintained between the components. A heated vacuum press was used to guarantee that the test samples were exposed to constant pressure throughout the bonding process. The press was heated up to a temperature of 120°F for bonding.

(U) Two types of test panels were fabricated: panels constructed with “clean” tiles and panels constructed with “defect” tiles. These panels were tested so that V50 data was acquired at triple point (TP) locations. The test panels were impacted at five locations at a constant velocity in order to calculate the V50s (see figure 2). Only five impacts were placed into each panel when testing triple points and the impacts were spaced. This is so that data could be acquired in areas of the panel with minimum damage. In other words, impacts were placed in areas of the panel where previous impacts would not have a large effect on the results. Panels were also tested at a constant velocity so that fluctuations in the velocity would not affect the results. For example, if the first impact was at an extremely high velocity it could affect the result of the next impact. The next impact at a lower velocity could penetrate to the extreme damage caused by the first impact. The idea of testing each panel at constant velocity and then varying the velocity between panels allows a V50 to be calculated for a system as opposed to a V50 being calculated for each individual panel.

(U) Samples were constructed with both “clean” and “defect” tiles to compare performance. Two different threats (Threat “A” & “B”) were examined in an effort to identify the sensitivity of flaws in the tiles to different types of threats. The specific threats were not identified since the detailed information of the threats was not necessary to demonstrate the concepts.

Figure 2. Triple Point impact locations (U)

(U) Data Analysis & Results

(U) This study was prompted by work which involved the evaluation of different supplier's high purity aluminum oxide ceramics. Initial data on the ballistic performance was gathered for sample panels which represented a full scale armor panel. The samples were made from 0.330"x2.0"x2.0" tiles bonded in a non-staggered array onto 0.250" thick 5083-H321 Aluminum. The ballistic limit (or V50) was established for center tile impacts and for seam impacts with threat "A". There was a clear difference established between the "best" performing tiles (Ferro manufactured) and the "worst" tiles as can be seen in figure 3.

Figure 3. Initial ballistic performance for "clean" & "defect" tiles (U)

The outcome of the supplier evaluation led to this follow-on study by posing several questions.

1. What is the cause of the variation in performance (assuming that the tiles were manufactured via the same processing techniques).
2. Can the cause be identified and quantified in some other ways and can those methods be used in standard quality assurance procedures.

The first obvious approach to understanding the variation of performance was a visual examination of the tiles. The "defect" tiles shown in figure 4 had very poor appearance as compared to the clean (see figure 5). There were a number of surface and sub-surface discolorations present in the "defect" tiles. These discolorations are probably due to contaminants from the tooling used to press the tiles prior to sintering.

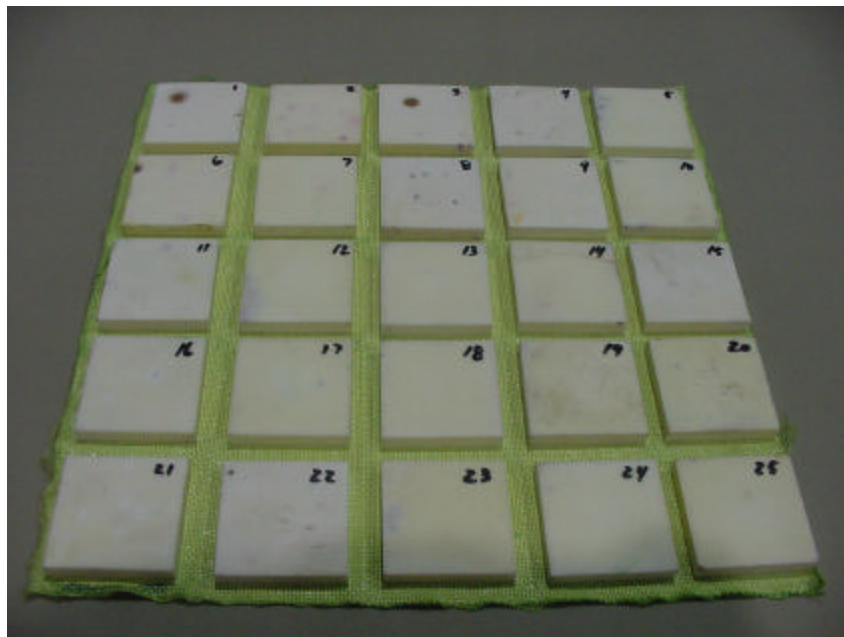


Figure 4. “Defect” Aluminum Oxide tiles (U)

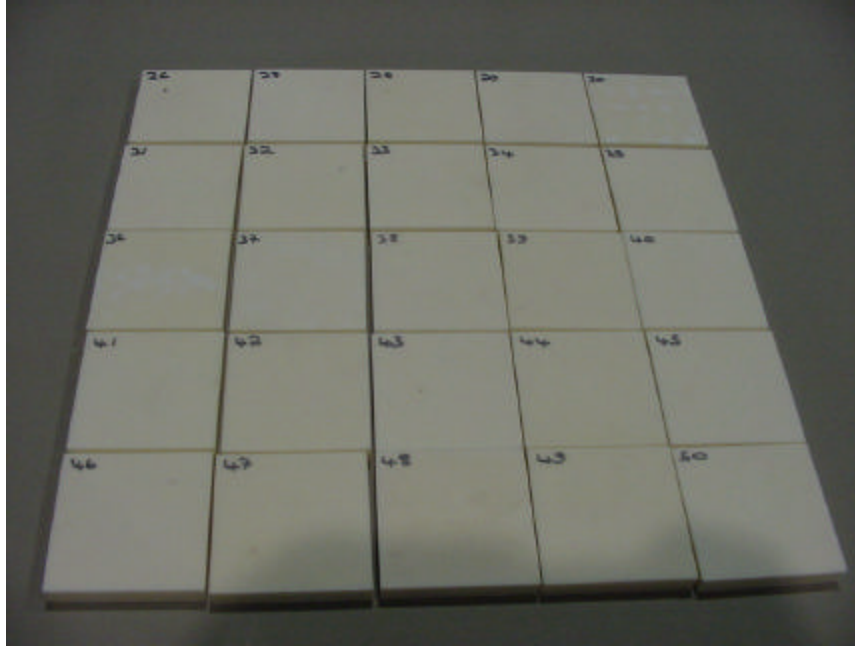


Figure 5. “Clean” Aluminum Oxide tiles (U)

Figure 6. Ultrasonic mapping of “defect” tiles (U)

Figure 7. Ultrasonic mapping of “clean” tiles (U)

In addition to visual inspection, the tiles were examined by x-ray photography and by ultrasonic mapping. The results for the ultrasonic mapping are shown in figure 6 and figure 7 for 25 each of the “defect” and “clean” tiles respectively. The x-ray photographs are not shown because they could not be converted to digital images in time for submission of this paper. There is a distinct difference in the results of the mapping for the “defect” and “clean” tiles. The defect tiles (see figure 6) show many small isolated areas with a 20-30% loss in signal return. These are probably due to small foreign particles, voids or low density regions at some depth in the tiles. In addition, there are large regions of nearly total signal loss for approximately 30% of the “defect” tiles examined. These may be due to large scale voids or fissures. It should also be noted that some of the mapping discrepancies can be correlated with visual appearance as in “defect” tiles marked 1 & 3. However, many of the defects which appear on the ultrasonic mapping are not visible on the tile surface. Although not shown, the x-ray photographs of the same tile layouts displayed only some of the same defects as the ultrasonic mapping but not all of them. The small scale defects may have been too subtle

to pick up on x-ray. The large scale defects may have been due to a discontinuity in a horizontal plane which is blind to the x-ray photo in the direction taken but which may be revealed in a x-ray taken from the side of the tile. The ultrasonic mapping of the “clean” tiles (figure 7) show very few small scale defects and a few rare cases of large scale defects (estimated less than 0.5%).

(U) Thus, a distinct correlation is shown between a set of tiles with a high number of defects and the lack of ballistic performance for armor systems constructed with those tiles (figure 6). The difference in performance between the “clean” and “defect” tiles appears to be greater for the seam impacts than for the center tile impacts. This may be due to the fact that there is more occurrence of the large scale defects near the edges of the “defect” tiles surveyed (see figure 6). It may also be attributed to the sensitivity of the system performance to the defect and shot locations. In other words, the center tile impact location has 360 degrees of continuous ceramic material surrounding it and is therefore less susceptible to the effects of a major or minor defect. Conversely, the seam has only 180 degrees of continuous ceramic material surrounding it (on each side) and the presence of a defect may have greater adverse effects. The limited data here does not support either hypothesis. Further, no effort will be made here to correlate these results to the complex dynamics which take place during an impact event.

(U) The additional samples constructed specifically for this work served two roles. First, an effort was made to re-verify the lack of ballistic performance associated with the “defect” tiles built into a slightly different construction (staggered array with 0.375” 5083-H321 aluminum backer). Second, a method for ballistic testing and data analysis is presented which provides more insight into multi-hit performance of ceramic systems as compared to conventional methods.

(U) The approach of selecting an identical shot pattern for every sample target and then shooting every shot on each target at constant velocity allows the data to be evaluated on a per shot basis. Figure 8 shows the distribution of shots on one of the targets after the front cover has been removed. The primary damage for each shot appears to be limited to the three tiles struck by the projectile. It is often assumed that the system is undamaged in a remote location away from the impact site. For example, the initial compressive shock wave resulting from the impact is damped and reflected as it moves laterally and crosses interfaces of the tile through the web adhesive to adjacent tiles. However, this is likely to be untrue due to the dynamic response of the entire system to each impact. The dynamic response is high rate flexure of the components which may be in different directions at any given time and location. The flexure of the entire system may cause cracking of the tiles and/or destruction of the bondline between the tiles and the backer at any location in the panel. The amount of destruction is also dependent on the choice of materials, how the sample is constrained in the test fixture, etc. In any case, the ballistic performance may decrease with each subsequent shot.



Figure 8. Shot target made with “clean” tiles (U)

(U) Figure 9 shows the data from 5 “clean” tile samples and 2 “defect” tile samples for threat “A”. The performance is plotted as a function of not only velocity but shot # or location. The partial penetrations (PP) are shown in green (light) symbols and the complete penetrations (CP) are shown in red (dark) symbols. There appears to be a trend of decreasing ballistic performance with increasing shots into the panel. An assumption is being made that the impact location with respect to the edges and consequently the mounting of the sample has minor effects of the performance. The dotted line is a “theoretical” trendline for the Ballistic Limit or V50. To refine the trend and create an actual V50 would require a significant amount of additional testing. There does not appear to be a difference in the performance between the “defect” samples and the “clean” samples for this system configuration. The primary difference between the initial targets which showed a difference in performance and the current system are: tile layout (staggered vs. non-staggered), thickness of the backer (0.375” vs. 0.250”) and the shot location (triple point vs. center tile and seam). It is believed that the difference in the thickness of the backer may be the primary cause. The change to a thicker backer raised the entire performance of the system such that the triple point V50 of the new system was comparable to the V50 for the center tile impacts of the initial system. The thicker backer changed the roles each component played in defeating the threat. In the current system, the 0.375” aluminum backer played a more significant role in defeating the threat such that the small scale tile defects may be less noticed.

Figure 9. System performance against Threat “A” (U)

(U) In an effort to examine the sensitivity of the system to various threats, 4 “clean” tile sample targets and 2 “defect” tile targets were built and tested for threat “B”. Threat “B” differed from Threat “A” in the bullet composition and the mass of the bullet and therefore different penetration characteristics against the ceramic system. There appeared to be much larger scatter in the data for Threat “B” (see figure 10). However, plotting the trendline just below the lowest complete penetration (CP) suggests that there may be a continuous degradation of the target with each subsequent shot. This system also did not appear to be susceptible to the small scale tile defects as no difference is evident between the “defect” sample data and the “clean” sample data. Again, it is recognized that more data is necessary to refine these trends.

(U) It is believed that large scale flaws should have a more significant effect on ballistic performance than what is shown for the current system. As mentioned, almost 30% of the “defect” tiles had large scale flaws as depicted by the ultrasonic mapping. Perhaps the flaws were never built into critical locations of the samples with respect to the impact sites. Although no testing has been done to date where the specific tiles with large scale flaws are built into the impact locations of the test samples, that work is currently underway.

Figure 10. System performance against Threat “B” (U)

(U) Conclusions

(U) Ceramic armor systems are inherently complex due to the many components in their makeup and the number of production steps from raw materials to finished product (armor panel). Equally complex is the evaluation of their performance. This is mainly due to the fact that the performance is location dependent and because multiple impacts progressively deteriorate the system. The concept for performance evaluation presented here can be applied to any system, threat and shot pattern. It is useful in revealing more detailed information about the overall performance with minimal to no increase in testing costs.

(U) Another aspect of complexity involves the quality of ceramic tiles themselves. The use of ultrasonic mapping is a low cost method for identifying defects. Ultrasonic mapping shows much higher resolution of discrepancies than visual inspection and x-ray. The effect of defects on ballistic performance is sensitive to the location of the defects, the impact sites, the target configuration and the threat type. It is recommended that ultrasonic mapping be used as a method of initially screening new tiles to determine the sensitivity of each specific application to flaws in the tiles as well as statistical inspection of ongoing production. However, significant questions still remain as related to “what is acceptable?”. While the answer to this question is strongly dependent on the specific application, it is not likely to be answered in a general sense without significant testing.